29-07-2012

Chapter 2

A synthesis framework for runoff predictions in ungauged basins

Contributors: T. Wagener*, G. Blöschl, D. C. Goodrich, H. V. Gupta, M. Sivapalan, Y. Tachikawa, P. A. Troch, and M. Weiler

*coordinating contributor

2.1 Catchments are complex systems

2.1.1 Co-evolution of catchment characteristics

Landscapes present amazing patterns that appear to be ubiquitous at any scale one looks. At the pore scale, microbes colonize soil particles and form biofilms that alter water flow paths and water-sediment contact time, thus affecting geochemical weathering and the nucleation of secondary minerals. Biogeochemical alteration of the mineral-water interface results in stable particle aggregates allowing the fast movement of water in interconnected flow paths. At the patch scale, rills form in response to rain splash erosive action and overland flow redistributes important nutrients and carbon that affect soil properties, such as infiltration capacity. Vegetation responds to this spatial variability in water and nutrient availability to form clusters characteristic of the dominant flow processes. At the hillslope scale, clear patterns emerge in soil characteristics as a result of the interplay of water and carbon movement, erosion, soil formation and both vegetation and animal action. At the landscape scale, the interplay of land uplifting and erosion-deposition processes generate landforms that feed back to ecological and pedological processes. At the same time, climate interacts with vegetation, soils and landforms through hydrologic processes to produce large-scale vegetation patterns. It stands to reason that the co-evolution of climate, vegetation and soils at the landscape scale leads to specific hydrologic partitioning reflected in runoff records. The satellite image of the landscape in the Channel Country in south-western Queensland shown in Fig. 2.1 illustrates the complexity of the landscape patterns where an intricate network of riverbeds has evolved in the alluvial fans made mostly of clays (Baker, 1986). Many of the challenges highlighted in Chapter 1 could be addressed if these landscape patterns could be connected quantitatively to catchment hydrologic response.

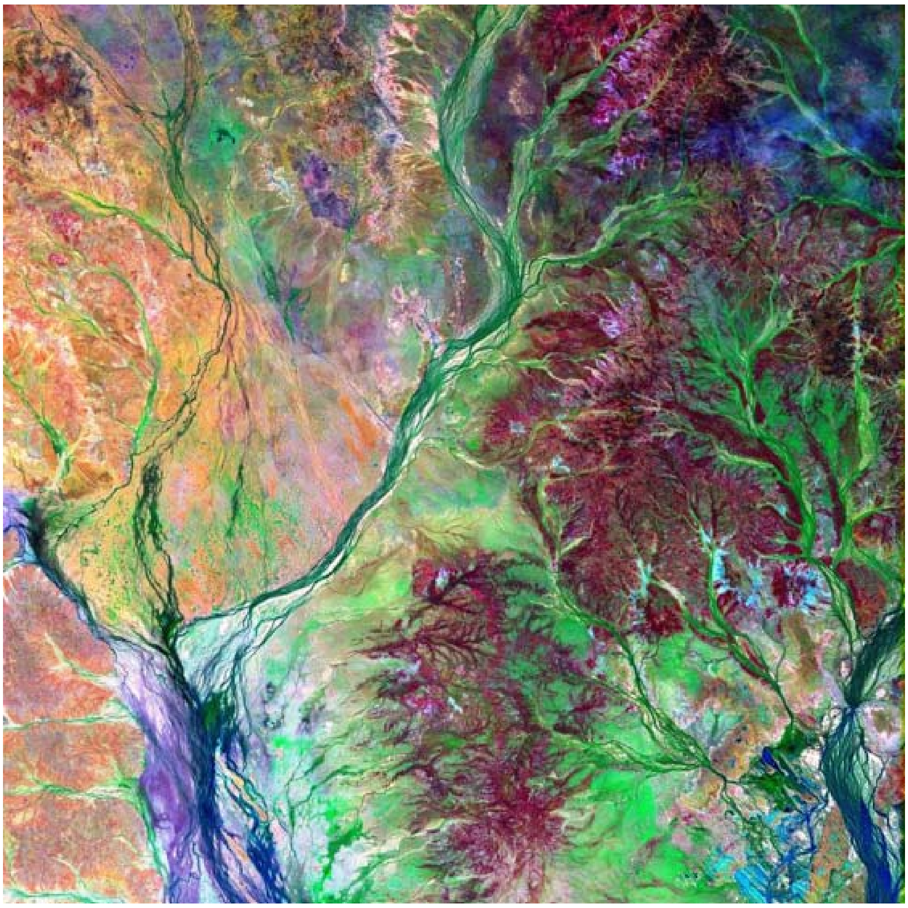

Fig. 2.1 Channel Country in south-western Queensland, Australia as a false-colour composite image of Landsat 7's ETM+ sensor on January 10, 2000.

Taken from biology, the concept of co-evolution refers to the process of reciprocal evolutionary change between interacting species, driven by natural selection (Thompson, 1994). In the case of catchments, co-evolution implies a process of reciprocal evolutionary change of soils, vegetation and topography, mediated by material and energy fluxes, in response to fast climate dynamics and slow geologic processes. The patterns that emerge reflect the legacy of past processes, their interconnections over a long period of time leading to the complex spatial patterns that we see in the landscape (Sivapalan, 2005). These spatial patterns are also responsible for the temporal patterns in runoff response, but the connection between these spatial and temporal patterns is still poorly understood. Jefferson et al. (2010) presents an example of this in Oregon, the net effects of co-evolution and hydrology in the basalt landscape in the Oregon Cascade Range in USA. They showed how dominant runoff processes change in catchments on lava flows having different ages. Younger catchments exhibit subdued response to precipitation as most water infiltrates and percolates into the permeable bedrock, recharging deep aquifers that generate runoff through permanent springs. Older catchments, on the other hand, have deeper soils with shallow clay layers that create an impeding layer, blocking infiltrated water from recharging the aquifers and instead cause shallow subsurface flow that quickly enters the channel network during rain events. At the landscape scale, this change in dominant flow processes causes more incision and a higher drainage density. This in a nutshell is the process of co-evolution as it applies to hydrology. Humans often play an important role in altering landscape characteristics, wherein their activities in some environments depend on water availability and through their actions they also affect the water availability (Sivapalan et al., 2012). The co-evolution of processes that have led to landscape patterns and their relationship to temporal and spatial patterns of hydrologic response is a key to a broader understanding of hydrologic response, including under human induced changes.

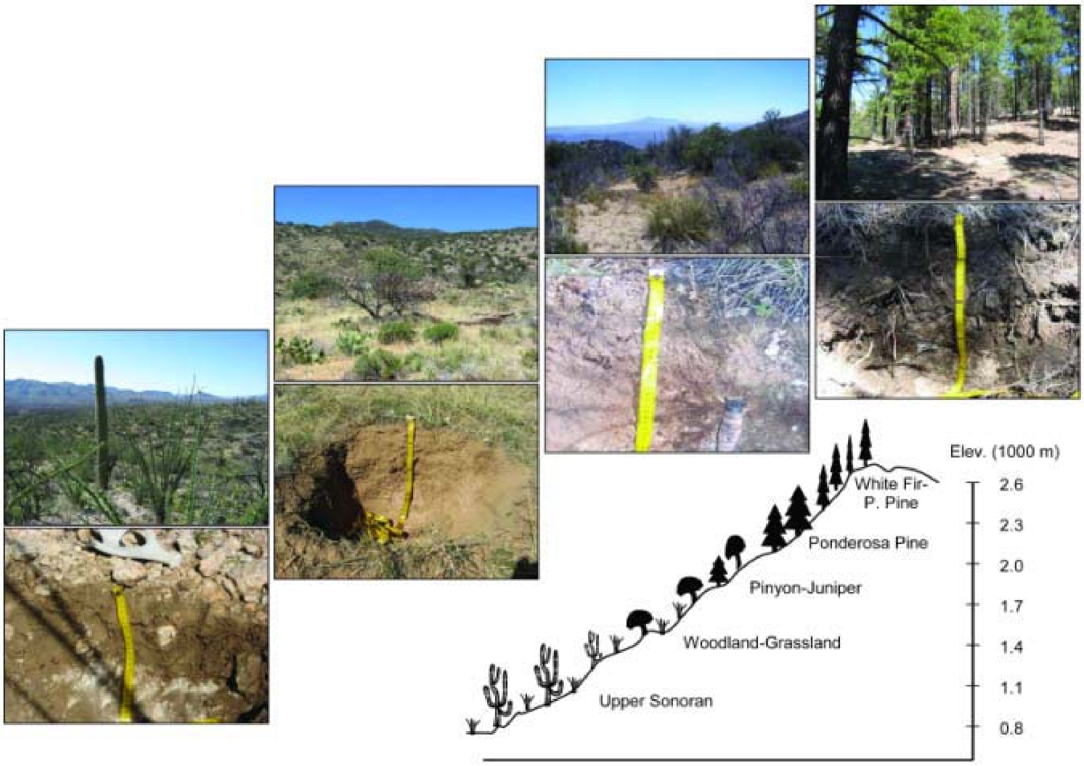

Figure 2.2: Soil-ecosystem evolution along a climate gradient in the south-western USA. From Rasmussen (2008).

Because of the coupling between different processes across many spatial and temporal scales, catchments are complex systems (Rihani, 2002; Kumar, 2007; Raupach et al., 2005). These are systems with a large number of strongly interdependent variables at many space and time scales. Complex systems are different from simple systems that contain a small number of dimensions only, such as simple mechanical systems. Simple systems are predictable in a deterministic sense and have limited complexity. Complex systems are also different from random systems with a very large number of dimensions, such as a gas. Random systems are predictable in a statistical sense and the traces may be complex at the molecular scale, but as one goes up in scale the variability averages out (Dooge, 1986).

A simple illustration of the difference between simple systems and complex systems is presented in Figure 2.3, in relation to flood processes and flood estimation in Austria. The left panel on Fig. 2.3 illustrates a traditional reductionist way of relating precipitation and catchment time scales to the flood time scale. The flood response time is the sum of storm duration and catchment response time. But in real catchments, these three time scales are not independent (Figure 2.3, right panel) and the interplay amongst them can be interpreted differently at different time scales, from hours to millennia. The events that produce the maximum annual floods are those for which the storm duration is close to the concentration time of the catchment, because the catchment response time scales filter the distribution of all storms to produce the distribution of flood producing storms. This is the reasoning behind the rational method for flood estimation and it applies at the event scale. At the seasonal time scale flood characteristics tend to be closely related to the seasonal water balance and, conversely, runoff event types affect the seasonal water balance through rainfall and snowmelt. At the time scales of decades, however, the flow paths as well as soil moisture affect erosion during floods and soil evolution (modulated by differences in geology), while soil depth and permeability affect flow paths and therefore the flood response at the event scale. Even at the landscape evolution time scales there are further interactions. Gaàl et al. (2012) illustrated how the comparison of catchments of contrasting characteristics can help to recognise the combined effect and interplay of flood processes on the landscape. They showed, for example, one catchment whose form has adapted to the flashiness of floods producing efficient drainage networks, which in turn enhance the flashiness of the flood response. In other catchments tortuous drainage networks have evolved, which in turn retard the flood response and impedes the evolution of an efficient drainage network.

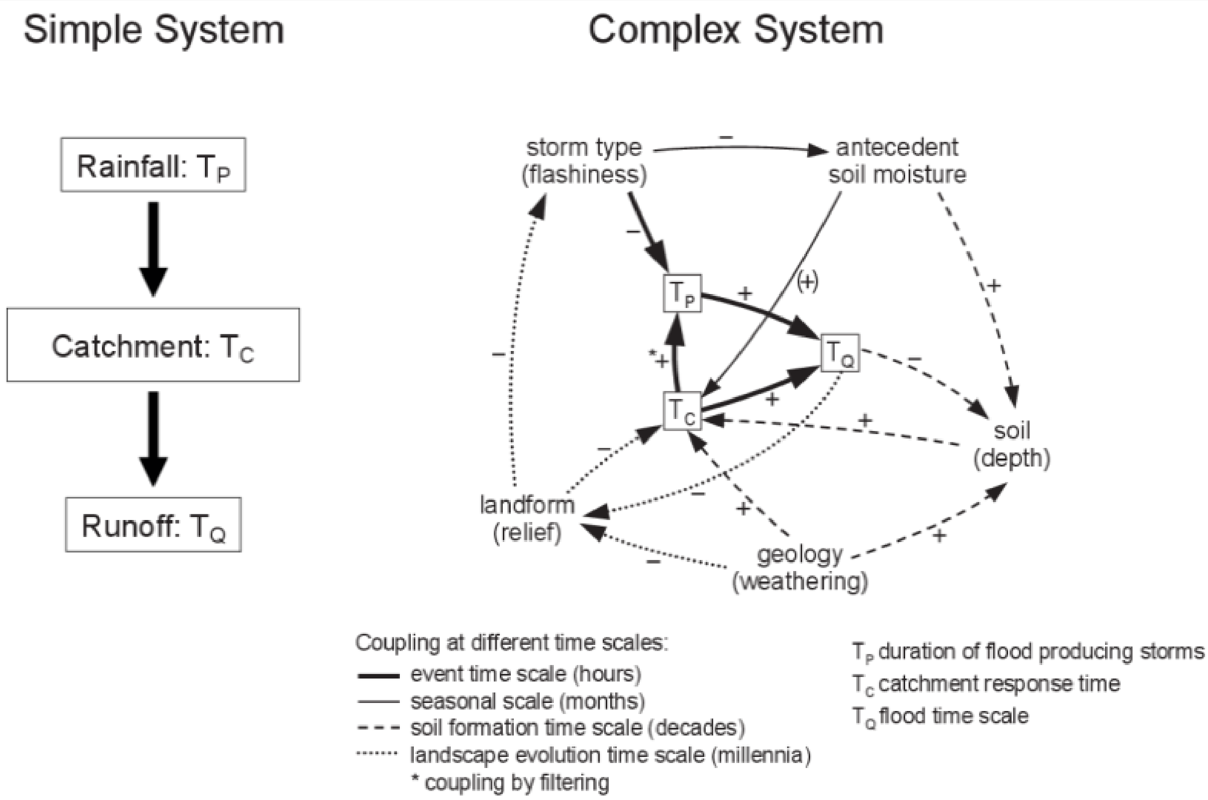

Figure 2.3 Simple and complex system representation of the time scales of floods and their process controls. Interactions of the processes at different time scales have been gleaned from comparative hydrology. From Gaál et al., (2012).

Complex systems are notoriously difficult to understand, and exhibit inherent limits to their predictability (Kumar, 2011). The complex interactions and feedbacks of the various component processes occurring within a catchment make it difficult to connect cause and effect in a straightforward manner, thus presenting a significant challenge to predictions in ungauged basins. On the other hand, an important feature of complex systems, as outlined above, is their tendency to generate emergent patterns. Depending on the scale one looks at the patterns the system produces may be different. If one zooms in, one set of patterns emerges. If one zooms out, a new set of patterns emerges. Being emergent patterns one cannot easily find causal connections between the patterns at different scales. In the catena example above, it is not trivial to explain how the interactions of local scale processes led to catena patterns at the hillslope scale, and further organized patterns around the river network at the catchment scale. The evolution of these patterns is the result of the interaction of several component processes at a range of space and time scales, producing patterns at many space scales (Fig. 2.2). Yet, the fact that catchments as complex systems create interesting spatial and temporal patterns, offers opportunities that can be exploited to advance predictions.

2.1.2 Signatures – a manifestation of co-evolution

Spatial patterns such as those presented in Figs. 2.1 and 2.2 are readily observable, and they contribute to observed temporal patterns of hydrologic response produced by catchments. Most importantly, the observed runoff response of a catchment constitutes an interesting, complex temporal pattern of water fluxes, which are the result of the collective behaviour of a great number of components of the catchment, including the effects of the landscape patterns.

When looking at the catchment behaviour in an aggregate way, one can identify typical, holistic characteristics of the catchment response, something termed catchment functioning by Black (1997), in analogy to a similar term used in ecology (Jax, 2005). The collective or holistic response of the catchment resulting from the component processes can be expressed in terms of holistic behaviours such as partitioning, transmission, storage and release of water, energy and matter (Black, 1997; Wagener et al, 2007; McDonnell et al., 2007). Partitioning refers to the separation of water, energy, and matter into different pathways at or near the land surface through processes including interception, infiltration, and surface runoff. Storage refers to actions of the catchment to retain water, energy, and matter in different parts of the catchment and over very different time scales. Storages can include snow and ice, interception, soil moisture, aquifers, water bodies, and also storage in vegetation. Transmission refers to the fluxes of water, energy and matter through the catchment. These fluxes are strongly dependent on the connectivity between the different parts of the catchment and will significantly vary over time in many cases, depending on the moisture state of the system. Finally, release refers to the mechanisms by which water, energy, and matter are released from the catchment through atmospheric, surface, and subsurface fluxes. Fluxes of water, energy, and matter include evaporation, transpiration, channel flow, sediment transport, and groundwater exchange.

The co-evolution of climate, vegetation, landscape and soils, through the self-organised landscape patterns it tends to produce, gives rise to evident fingerprints on the catchment runoff responses. Since the structure of the landscape determines the heterogeneity and organisation of pathways that water can follow, and associated residence times, these also govern the richness of the catchment's hydrologic responses. This includes the emergent connectivity of pathways, the appearance of thresholds and tipping points, all leading to a holistic response that is harder to prescribe *a priori*, let alone predict on the basis of traditional simple system approaches. Indeed, Knighton and Nanson (2001) have documented complex patterns of event-scale runoff variability at a range of time and space scales for the Channel Country of Australia, including Lake Eyre in Australia, which overlaps with the geographic region presented earlier in Fig. 2.1. It raises interesting questions about how the amazingly complex spatial patterns shown in Fig. 2.1 are mirrored in the runoff variability, and whether it can be explained hydrologically to enable predictions. Understanding these connections is particularly important when humans increasingly become a major part of this co-evolutionary system, with the possibility of generation of new emergent dynamics hitherto unobserved (Winder et al., 2005; Kallis, 2007).

In this book, following Jothityangkoon et al. (2001) and Eder et al. (2003), the temporal patterns of observed runoff response of catchments, when viewed at different time scales, are termed runoff "signatures", and are deemed as emergent patterns. We term them signatures because they are considered as reflections of the overall functioning of the catchment, including the co-evolutionary features of the catchment's surface and subsurface architecture. The spatial signatures of catchments, such as soil catena, stream network topology, and soil moisture patterns, are all intimately related to the temporal patterns of runoff at different time scales, and the focus here is on advancing and exploiting our understanding of their interrelationships.

Runoff variability at any location is a temporal continuum covering a wide range of time scales, but the characteristics one sees depend on the temporal scale one chooses to look at. This is because catchments exhibit the characteristics of complex systems, so different patterns emerge at different time scales. At time scales of seconds one may recognise the effects of turbulence and wave action in the runoff. At time scales of millennia, if such data were available as in the case of Jefferson et al. (2010), one would recognise long-term climate and landscape evolution trends. There may be several emergent patterns in the time domain and they are all inter-connected because they are all the result of the same complex system and co-evolutionary processes.

Depending on the collective behaviour of the catchment processes and the underlying drivers, the runoff signatures may differ. Therefore they can be seen as windows that enable us to look into the catchment dynamics at different time scales. They help us to understand the system holistically. Signatures provide insights into catchment processes, and are thus outward manifestations of the internal dynamics of the catchment. The runoff signatures examined in this book are annual runoff, seasonal runoff, flow duration curves, low flows, floods and runoff hydrographs (Fig. 2.4). In a preface to a special journal issue on the downward approach to hydrologic prediction, Sivapalan et al. (2003) said, *inter alia*, that "… the Budyko curve, inter-annual and mean monthly variability of water balance, flow duration curves, and the spatial organization of these signatures … are the key signatures that embody the hydrologic organization or hidden order, and a quest for identifying them seems promising…..". For example, annual runoff is a reflection of the catchment dynamics at relatively long time scales, which is particularly evident in the between-year variability of annual runoff. Seasonal runoff reflects the within-year variability, i.e. how the catchment organises itself at the sub-annual time scale. The flow duration curve represents the full spectrum of variability in terms of their magnitudes. Low flows focus on the low end of that spectrum, and so provide a window into catchment dynamics when there is little water in the system, and floods are at the opposite end, when there is much water in the system. Hydrographs are the complex combination of all of these signatures. They are the most detailed signatures of how catchments respond to water and energy inputs.

In this book the signatures are the starting point for making runoff predictions in ungauged basins as they are the fingerprints of the catchment functioning at different time scales. They are also the focal point of the predictions, and predictions of all the signatures in ungauged basins are reviewed in this book in their own right. In fact, they are fully consistent with the time scales at which runoff predictions in ungauged basins are needed from a societal perspective, as illustrated in Table 1.1.

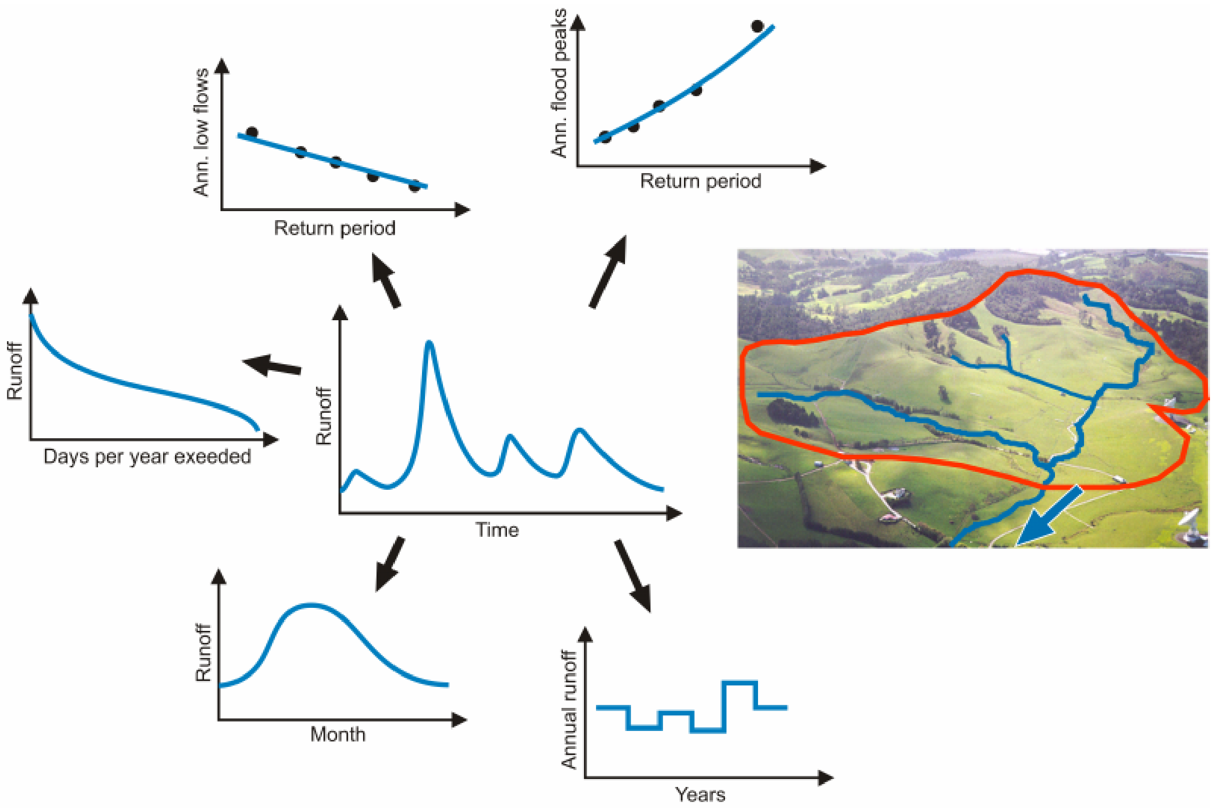

Fig. 2.4 Runoff signatures examined in this book. Clockwise from bottom right: annual runoff, seasonal runoff, flow duration curves, low flows, floods, runoff hydrographs. Photo: R. Young.

2.2 Comparative Hydrology and the Darwinian approach

2.2.1 Generalisation through comparative hydrology

One way of learning from the runoff signature patterns is to build models based on Newtonian mechanics that can represent the component processes in a particular catchment in considerable detail. These models can then be used to perform simulations over several years (or decades) to see whether they match the patterns observed in natural catchments (e.g., Carrillo et al., 2011). Similar detailed mechanistic models can also be built to simulate hydrological processes over shorter time scales in order to predict rainfall-runoff response in ungauged basins. The strength of these mechanistic models is that the causality of the component processes can be represented in a deterministic way and in much detail, although it is inherently much more difficult to represent well the feedbacks between different processes acting at a range of time scales. It is this aspect of complex systems that contributes to their limited predictability. Modelling the interactions and feedbacks between different processes acting within catchments may be improved if we better understand the effects of co-evolution of climate, vegetation, landform and soils on catchment functioning.

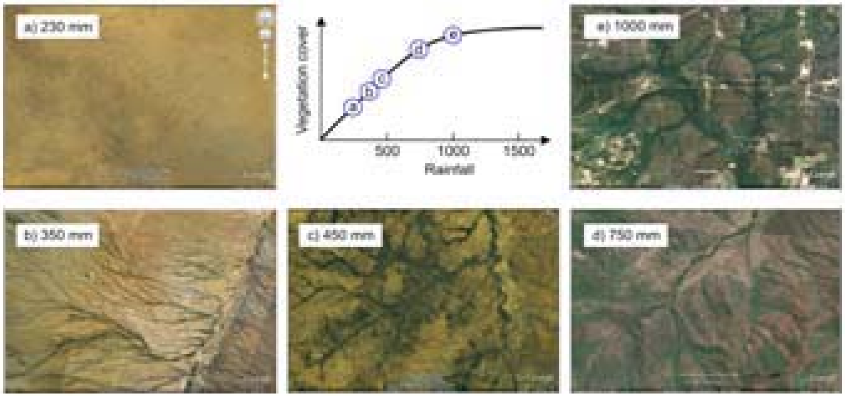

Fig. 2.5 Vegetation patterns for different regions in Australia with annual precipitation ranging from 230 to 1000 mm. From Thompson et al. (2011).

Instead of studying a particular catchment in much detail, an alternative approach may be to examine many catchments at the same time and study the emergent patterns in a comparative way. Here, the purpose is to develop *generalisations* beyond individual catchments by learning from differences between many catchments which are deemed as legacies of co-evolution. There is a lot of potential for this type of comparative analysis. Fig. 2.5 illustrates the idea for regions in Australia with different precipitation availability. Under sufficiently arid conditions (a) almost all precipitation evaporates, and hydrological processes are essentially vertical, producing sparse vegetation organised in spotty spatial patterns. As precipitation availability increases (b and c), horizontal flow processes become increasingly important and perennial vegetation emerges in close association with the drainage network structure. At even higher precipitation rates (d and e) canopies begin to close and woody vegetation occupies most of the catchment but there may yet be differences in the species between drainage lines and the uplands. Process based models of the Newtonian type could also produce these patterns, but it is unclear how to parameterize these process based models across climate gradients to reflect changes in dominant hydrologic processes that help generate the spatial patterns. By doing comparative analysis across these diverse regions, i.e. exploiting the differences in the patterns, one may be able to infer the controls on the landscape processes at the long time scales of vegetation adaptation, and build appropriate models that reflect such controls.

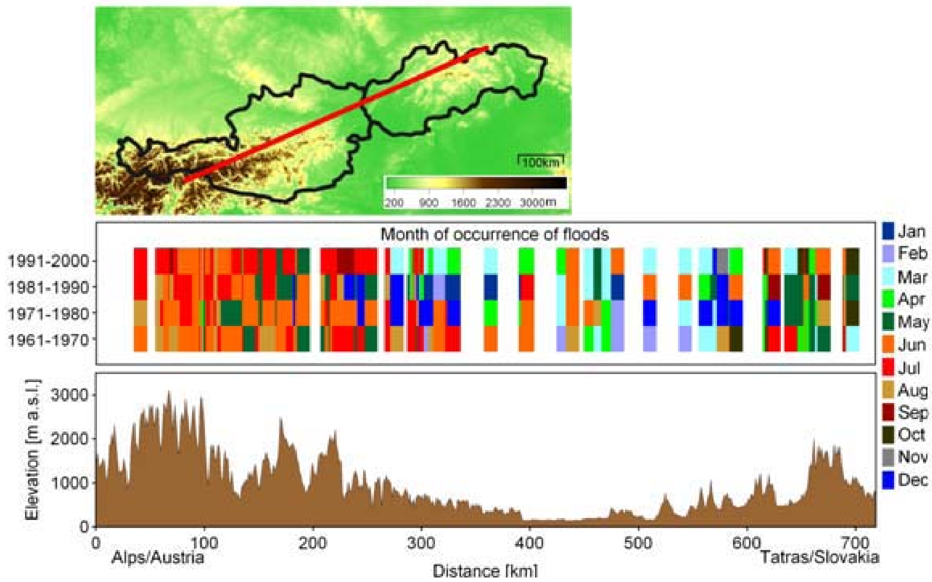

Fig. 2.6: Season (month) of the occurrence of floods along a transect Austria – Slovakia in decades of the period 1961–2000. Bottom panel shows the elevations of the transect. From Parajka et al. (2009).

Fig. 2.6 shows another example to illustrate what can be learned though comparing and contrasting many catchments, knowledge that is impossible to obtain otherwise. It presents along a transect across Austria and Slovakia the time of the year that floods have occurred, revealing interesting differences and similarities, even though most of the precipitation occurs in summer in the entire region. In the Alpine catchments in the west floods are summer dominated while in the lowland catchments in the centre of the cross section winter floods dominate. This is because of the seasonal interplay of soil moisture dynamics and flood generation processes. In summer, the lowland soils tend to be very dry while in winter they are much wetter, thus favouring flood occurrence. It is also interesting to see how winter floods move further up in elevation as the climate gets warmer (at location 300km).

The approach of analysing many catchments in a synoptic way, as in the two previous examples, has been termed "comparative hydrology" by Falkenmark and Chapman (1989). Rather than modelling a single catchment in detail, the idea here is to compare many catchments with contrasting characteristics in order to understand the process controls of the catchments viewed as complex systems. Falkenmark and Chapman (1989, p.12) summarise their approach as follows: "The term 'comparative hydrology' was coined to describe the study of the character of hydrological processes as influenced by climate and the nature of the earth's surface and subsurface. Emphasis is placed on understanding the interactions between hydrology and the ecosystem, and determining to what extent hydrologic predictions may be transferred from one area to another". They note, however (p.9) that: "It should be remembered that the book represents no more than a first effort to draw attention to the field of comparative hydrology, and we sincerely hope that by doing so, further research in the field will be stimulated. In our understanding, comparative hydrology should develop into a basically analytical science. The heavy descriptive content in the late sections of this textbook should therefore be accepted as an infant disease, as few analytical studies stressing similarities and differences between hydrological zones are yet available." The present book builds on the comparative hydrology approach of Falkenmark and Chapman, and attempts to do so in a quantitative way to generalise beyond individual catchments.

One of the strengths of comparative hydrology is that it allows the examination of processes in a more **holistic** way than does normal modelling. In a model, only those processes and scales actually represented in the model can be analysed, while in the comparative hydrology approach we can see the summary effect and interplay of all relevant processes if the data from the catchments of contrasting characteristics are compared. Also, the comparative hydrology approach provides an opportunity to exploit multiple development histories. Different catchments have evolved in a different way as a result of different climates and geologies and that historical legacy is apparent at one time in many places. This concept can be illustrated by the example of the medical doctor in Fig. 1.5. Instead of dissecting each patient to look inside the body for the cause of a reported ailment, the doctor may choose to look around the world to see the case histories of a larger population of people with similar ailments before prescribing a treatment.

The comparative approach used for generalisation can be deemed a Darwinian approach. Charles Darwin conducted a comparative analysis of wildlife and fossils that he had collected during his world trip and came up with the principle of natural selection by generalising the patterns he saw in the record he assembled. As Sivapalan et al. (2011, p. 5) put it in a hydrological context: "The Darwinian approach values holistic understanding of the behaviour of the given landscape. It embraces the history of a given place, including those features that are relics of historical events, as central to understanding both its present and its future. The Darwinian approach gains predictive power by connecting a given site to several sites located along critical gradients. Laws in the Darwinian approach will seek to explain patterns of variability and commonality across several sites." The Darwinian approach therefore contrasts sharply with the Newtonian approach, which remains the dominant paradigm in physics, and even in hydrology, and builds on the application of universal laws (Harte, 2002). The Darwinian approach, on the other hand, is the dominant paradigm in ecology and emphasises patterns and the history of the place. Much of the insight and power of the Darwinian approach comes from comparing similar and dissimilar places and generalise, just as how Darwin learned from comparing species from around the world. Newtonian approach generalises by finding universal laws, the Darwinian approach generalises through discovering patterns through comparisons and asking questions of how they came about.

How then does the comparative hydrology approach **help** in the synthesis across processes, places and scales, the focus of this book? We consider each catchment as a result of nature's myriad experiments. Each catchment represents a sample, a distinct outcome, one of an infinite variety, but resulting from a combination of the same co-evolutionary earth system processes, and underpinned by common, yet unknown, organizing principles: water flow processes, land forming processes, and life sustaining processes. But these same organising principles may manifest themselves in different ways in different climates and geologies, so they may look randomly different. The comparative hydrology approach may be a useful framework to study these apparently random (or unique) catchments.

Just like a jig saw puzzle will look random at first, when it begins to fall into place it begins to reveal interesting patterns and indeed connections. In other words, the goal of comparative hydrology is to ultimately bring order into what otherwise looks disordered, find new connections where none existed, and will therefore be the hallmark of the synthesis we propose. The comparative hydrology approach will bring order into a diversity of hydrological processes, just the way Darwin found order amongst otherwise different species, or the way the periodic table of chemical elements brought order to a seemingly unrelated collection of chemical elements. The comparative hydrology approach will bring order into the diversity across places as it will help find patterns along spatial gradients of climate and landscape characteristics. And the comparative hydrology approach will bring order into the diversity across scales as the land surface is organised into catchments of all sizes, nested within each other, and different properties may then emerge at different scales that can be studied, interpreted and explained by the comparative hydrology approach. Bronowski (1956, p. 23) brilliantly described this natural, otherwise normal, scientific process in the following words: "All science is the search for unity in hidden likenesses…The progress of science is the discovery at each step of a new order which gives unity to what had long seemed unlike… For order does not display itself of itself; if it can be said to be there at all, it is not there for the mere looking… order must be discovered and, in a deep sense, it must be created. What we see, as we see it, is mere disorder."

2.2.2 Hydrologic similarity

The success of the comparative hydrology approach hinges on the concepts of similarity and dissimilarity. If one compares many catchments some of them will appear more similar with respect to a particular characteristic and this similarity will guide the interpretation of the different emergent patterns. Catchments can be considered hydrologically similar, in a general way, if they filter climate variability in similar fashion, as expressed by their (scaled) hydrologic signatures. This similarity may be brought about by similar trajectories of co-evolution of climate, vegetation, soils and landscape. The concept of similarity and dissimilarity of processes is illustrated in Figure 2.7. In arid catchments, there is relatively little precipitation, much of which evaporates, and there is little infiltration (and which is highly episodic) down to a deep aquifer. A part of the stream reaches will be losing reaches, with flow in the river infiltrating through the river bed to recharge the underlying aquifer. In contrast, in a humid catchment precipitation will be higher, and infiltration will be less episodic. A part of the stream reaches will be gaining reaches where the groundwater recharges the stream flow.

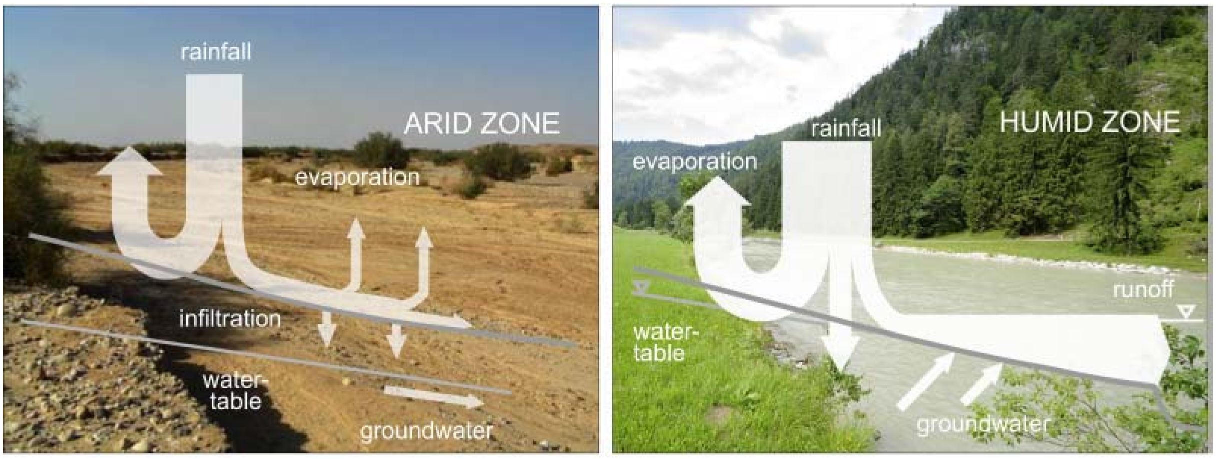

Figure 2.7 Runoff generation and surface water - groundwater interactions under typical arid and humid conditions. After Erhard-Cassegrain and Margat (1979) in Falkenmark and Chapman, (1989). Photos: (a) O. Dahan, (b) P. Haas.

Hydrologic similarity in terms of similarity of processes is difficult to identify in a real world setting as only partial knowledge of the hydrological processes is available. Based on the rationale that runoff is the result of the interplay of climate and catchment processes, one can therefore split up the more generic similarity into runoff similarity, climate similarity and catchment similarity (Fig. 2.8). The comparative hydrology approach then consists of learning from the similarities and differences of catchments in terms of their climate, catchment characteristics and runoff signatures. The underlying assumption is that catchments that are similar with respect to climate and catchment characteristics will also behave similar in a hydrological sense. This assumption can be tested in gauged catchments where one can learn from relating the runoff signatures to climate and catchment characteristics. In ungauged catchments one can use the concept of similarity to transpose what one has learned in gauged catchments in order to predict runoff in ungauged basins.

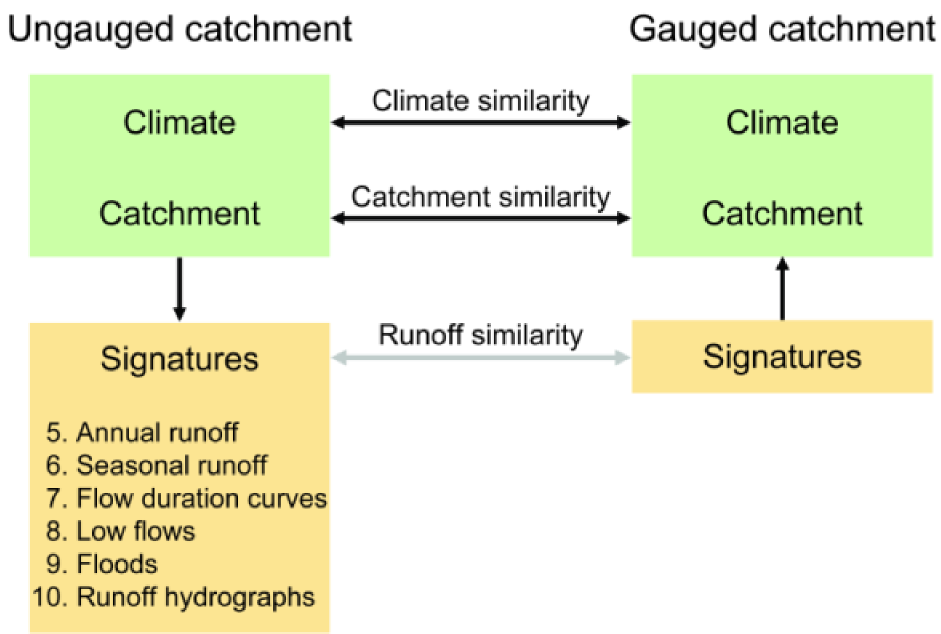

Figure 2.8**:** Prediction of runoff signatures in ungauged basins through climate, catchment and runoff similarity (the numbers in the box refer to the various chapters of this book).

Climatic similarity

Climate similarity, in the context of this book, entails similarity in climate characteristics that are relevant for hydrology. Climate classification schemes such as those by Köppen (1936) and Thornthwaite (1931) define regions through a combination of mean annual precipitation, air temperature and their seasonal variability. L'vovich (1979) and Budyko (1974) developed long-term average relationships between measures of water and energy availability in various regions. A typical index of this kind is the aridity index, which is the ratio of annual potential evaporation and annual precipitation. Those catchments with aridity indices larger than unity are deemed water limited, and those with an aridity index smaller than unity are energy limited. If the aridity indices are similar, the catchments are deemed similar with respect to the relative availability of water and energy. Catchment characteristics, such as soils, topography and vegetation, puzzlingly, only play a secondary role in this partitioning, which is suggestive of their co-evolution. Climate similarity can also be defined as similarity in the inter-annual variability of precipitation if one is interested in the long term fluctuations of runoff. Climate similarity can further be defined as similarity in the extreme rainfall and its seasonality if one is interested in floods, and in terms of dry spells and of their seasonality if one is interested in droughts and low flows. The relative importance of snow processes can be very relevant for hydrological similarity and these can be indexed by air temperature and/or catchment elevation.

Comparative hydrology sometimes discovers similarity indices and predictors that contradict or defy process interpretations. This may be because they represent several, not one, factors that contribute to the explanation of a variable of interest, and so mask the process interpretation. An example is mean annual precpitiation, which happens to be a powerful similarity index for flood peak, for example. It becomes a useful similarity index because of its direct effect on runoff generation at the event scale but through longer term soil moisture availability and still longer term landscape, soil and vegetation evolution processes. In other words, the value of mean annual precipiation as a climate similarity index for floods goes beyond the event scale causality, and reflects the net effects of co-evolutionary processes.

Catchment similarity

Catchment similarity, in the context of this book, entails similarity in those catchment characteristics that control runoff processes (McDonnell and Woods, 2004). From a catchment functioning perspective these are processes that control the partitioning, transmission, storage and release of water, so similarity relates to similarity in one or more of these functions. Catchment characteristics that relate to partitioning are infiltration properties of soils, such as hydraulic conductivity, which often is estimated with the use of pedo-transfer functions from soil texture. They also include vegetation indices, often as a proxy of evaporation at seasonal or annual time scales. Catchment characteristics that relate to transmission are those that represent flow paths in some way. One example is the topographic wetness index (upslope contributing area divided by the local surface topographic slope that provides similarity of the competition between hillslope recharge and drainage (Kirkby, 1978). Catchment characteristics that relate to storage are geology and soils properties such as soil depth. Also, area is sometimes used as a indicator of catchment storage as larger catchments tend to be more groundwater dominated with deeper flow paths and more active storage availability.

Many of the catchment processes occur below the surface, so similarity is difficult to quantify unambiguously. Co-evolutionary indices related to interacting catchment processes are therefore particularly important. The classical index is stream network density (stream length per area). The rationale behind the use of stream network density as a similarity index is that the stream network is itself a result of the co-evolution of the landscape, soil and vegetation, subject to the climate and geology in a particular region (Abrahams, 1984; Wang and Wu, 2012). Drainage densities tend to be the result of water availability (precipitation – evaporation), infiltration characteristics of the surface soils and the drainage characteristics of the underlying geology, which together determine how much runoff is generated and the fraction of surface runoff, and the armouring provided by the presence of vegetation. In this way, the drainage density is a holistic index combining a range of processes at a multitude of time scales, and thus reflects the overall catchment functioning. Hydrology clearly exhibits many similarities with geomorphology (de Boer, 1992). In a review of predictive modelling in geomorphology, Haff (1996) states, *inter alia*, “In geomorphic systems, 'empirical' variables that are found to be useful for prediction may in fact be related to emergent variables of the system. In such cases, searching for emergent variables, and the constitutive rules that connect them, should be a central focus of activity of geomorphological science,…. rather than scaling up the results of well-controlled laboratory-scale studies.” The photos in Fig. 2.9 show examples of how differently landscapes have evolved with similar total annual rainfall.

Xu et al. (2012) have found a Budyko type relationship between the ratio of deep-rooted vegetation to total vegetation cover across Australia is also governed by the same ratio of water and energy. It stands to reason that we can make progress in understanding other seemingly simple catchment responses, such as the baseflow recession, by focusing on the role of climate, vegetation, soil and landform interactions in governing this emergent simplicity. This is the rationale behind the organisation of the book.

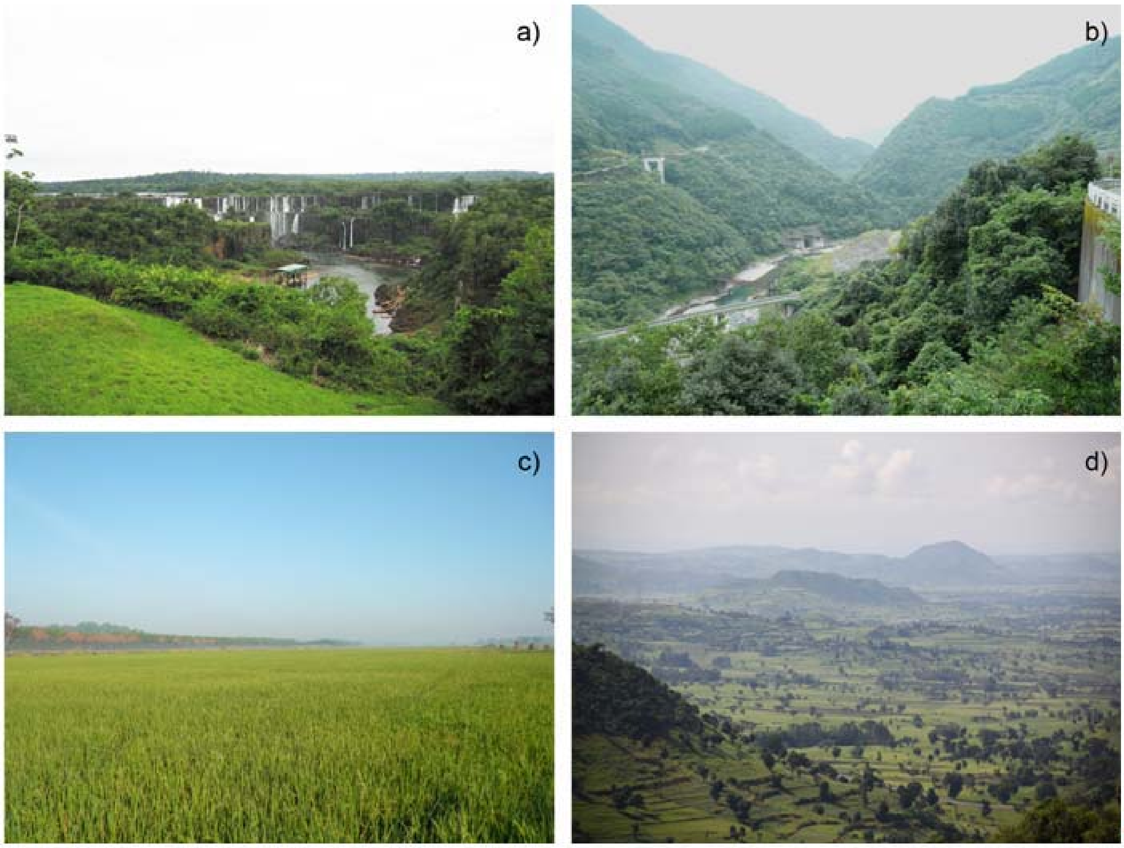

Figure 2.9: Climate and catchment similarities and dissimilarities: (a): Wet flat forest at Iguazu, mean annual precipitation P_A =1880mm/yr; Wet steep forest in the Kuma River in Japan, P_A =1990mm/yr; (c): Wet flat paddy at the Irrawaddy River basin in Myanmar. P_A =2500mm/yr. Photos: Y. Tachikawa; (d) Landscape in Ethiopia, P_A =Xmm/yr. Photo: A. Eder.

Runoff similarity

In the case of runoff similarity the interest resides in how similar or dissimilar the characteristics of runoff are. Within the framework of signatures as emergent patterns runoff similarity can therefore be defined as similarity in the runoff signatures. If one is interested in the long term hydrological behaviour, catchments would be considered similar if their "annual runoff signature" does not differ much. This may be the long term mean runoff (expressed as a fraction of precipitation), or alternatively, the variability of annual runoff between years (expressed in terms of say, elasticity). If one is interested in floods, catchments may be considered similar if their flood signatures, such as the flood frequency curve, exhibit similarities. Similarity does not necessarily imply that all the signatures are identical. Typically, similarity rests on scaled variables (Wagener, et al., 2007). For example, the flood frequency curves scaled by the mean annual flood may be considered the characteristic by which similar catchments should not differ by much. Two catchments could be similar in all signatures (which may be rare), but they could be similar in terms of one signature, say, low flow but dissimilar for others such as floods. This means, the runoff similarity may depend on the signature one is interested in. In other words, given the diversity of nature, one cannot expect there to be "perfect" similarity.

Indices of runoff similarity require runoff data to be available. For the case of ungauged basins runoff data clearly are not available. The similarity approach then uses the similarity of climate and catchment characteristics in order to infer hydrological similarity in an approximate way, and help predict runoff in ungauged basins.

Catchment grouping – exploiting the similarity concept for pub

Hydrological similarity between catchments can be exploited in two ways for runoff predictions in ungauged basins:

- to assist in the understanding of hydrological processes
- to transfer information from gauged to ungauged locations

Understanding of hydrological processes: Once the hydrological similarity or dissimilarity of catchments has been identified (for a particular purpose) the catchments can be grouped to reflect the similarity. These groups can then be used for classifying catchments. The power of classification can perhaps be best illustrated by the periodic table of chemical elements credited to Dmitri Mendeleev. Before Mendeleev's classification, the reactions of chemical elements must have appeared chaotic and confusing. Mendeleev's periodic table not only enabled him to better understand the behaviour of various chemical elements (e.g., on the basis of their atomic number) but he was also able to "predict" characteristics of chemical elements that were then unknown. In a similar fashion, classification can be used in hydrology for organising catchments, simplifying relationships and generalising findings. These may help with process based models, in particular to find out what types of models to use. This type of classification/grouping may also assist with assessing our predictive ability, e.g. in what kind of catchment is our predictive ability higher or lower. Ultimately this will assist with the generalisation issue that has haunted hydrologists since the science began.

Transferring information from gauged to ungauged locations: From a more practical point of view, similarity can be used to transfer information from gauged to ungauged locations. In a first step, catchments (or landscape units) are identified that are similar in terms of the climate and/or the catchment characteristics chosen and are grouped together. Usually some index is chosen that quantifies what makes two catchments similar in terms of climate (such as similar mean annual precipitation, P_A) and catchment characteristics (such as mean catchment elevation, Z). A distance measures then defines the similarity or dissimilarity between two catchments. A typically used distance measure is the Euclidian distance. In the examples above, the Euclidian distance is $D^2 = (P_{A,i} - P_{A,j})^2 + (Z_i - Z_j)^2$ (in fact, the indices could be scaled to make P_A and Z dimensionless, and in this way given them equal power). The important point here is that the distance D is small if the catchments are similar with respect of their catchment / climate characteristics. The catchments are then grouped into similar regions on the basis of minimising the distance measure D. The over-riding idea of grouping usually is that within the group the catchments should be as similar as possible, but the averages of the different groups should be as different as possible. This is illustrated in Fig. 2.10a where the catchments characteristics within each of the two regions are similar, and are different between the regions. There is a trade-off between the number of groups and the homogeneity within the group, the more groups one form the more homogeneous each of them will be, but a larger number of groups entails a relatively smaller number of catchments per group. There are numerous methods available for identifying homogeneous groups, which include cluster analysis and other multivariate statistical methods (see, eg. Cressie, 1991; Arabie et al., 1996). This grouping step breaks up the landscape into a mosaic of units that may or may not be contiguous. The rationale is that, if the climate/catchment characteristics are similar, the hydrological processes will also be similar. In a second step, this grouping is then exploited for regionalisation. For example, the grouping can be used to transfer the flow duration curve scaled by the mean annual flow from gauged to ungauged basins on the basis of the assumption that these scaled curves will be identical in the entire homogeneous region. Similarly, scaled flood frequency curves (i.e., growth curves) can be transferred from gauged to ungauged catchments based on similar assumptions.

Sometimes, however, one is not interested in finding groups of catchments that are most similar in terms of their climate/catchment characteristics but in terms of their mapping functions, i.e. the models that estimate runoff from climate and catchment characteristics. The mapping functions can be regressions between catchment characteristics (such as elevation) and runoff signatures (such as mean annual runoff). The mapping functions can also be process based rainfall-runoff methods. The important difference from the previous approach is that now we are not interested in finding regions that are homogeneous in terms of, say, mean annual runoff, but in terms of the regionalisation method, i.e. implying that that the same, say, regression model applies to all catchments within a region, but a different model in different regions. This is illustrated in Fig. 2.10b. The runoff signature S_Q (such as mean annual runoff) is estimated from climate characteristics, *Cl* and catchment characteristics, *Cc*, based on a model *f* (which can be a regression, a rainfall-runoff model, etc.). The model will then differ between the regions, i.e. in region 1, the $S_Q= f_1$ (*Cc*, *Cl*), in region 2, the $S_Q= f_2$ (*Cc*, *Cl*). Instead of *Cc* and *Cl* that were similar in the previous approach, now it is f_1, f_2 etc. that are similar within a group. In some instances the model *f* is process based using balance equations based on Newtonian mechanics. In other instances the model *f* does not resolve the processes in detail but exploits the co-evolution of catchments. For example, even if the runoff processes are not known in detail, a regression between stream network density and mean annual floods can give excellent results. However, the relationship between stream network density and mean annual floods may differ fundamentally between regions. In one region the low stream network density may be due to karst, in another region the low stream network density may be due to sandy soils, and in still another region it may be due to low precipitation. In these three regions the functional relationships *f* between stream network density and mean annual floods will be different. Identifying groups with similar regionalisation methods is less straightforward than those with similar catchment characteristics and, often, iterative methods are used.

Finally, the grouping of catchments is sometimes done on the basis of runoff. This may be useful as a first regionalisation step. However, to transfer the runoff signatures to ungauged catchments some sort of allocation rule is needed, i.e., information about what group a particular ungauged catchment belongs to. Allocation rules can, again, be estimated from runoff data and then use climate and catchment characteristics in the ungauged catchments.

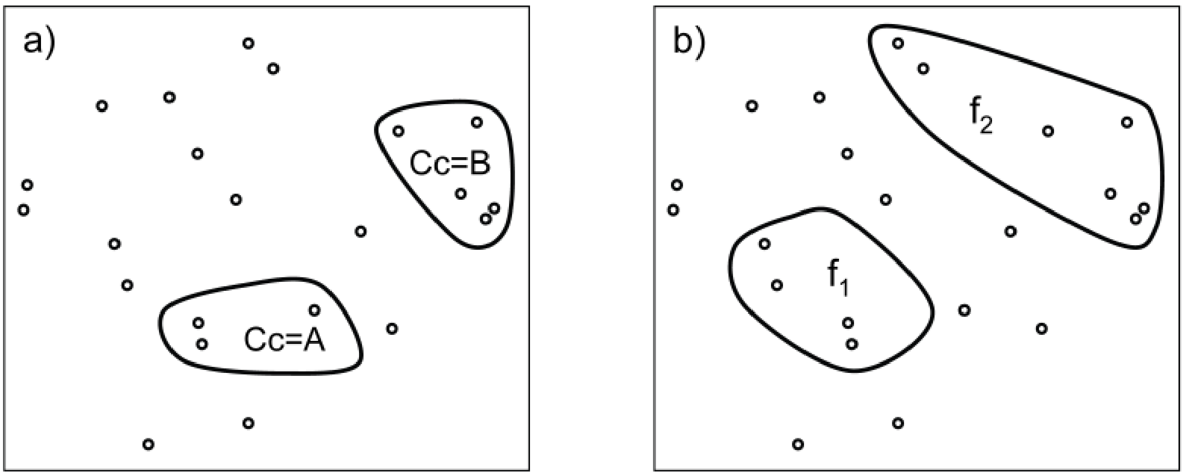

Fig. 2.10 Map of an imaginary country where catchments (indicated as points) are grouped into regions. (a) Grouping into regions with similar catchment characteristics, Cc; (b) Grouping into regions where the regionalisation methods f_1 and f_2 (such as the regression equations) are similar.

2.3 From comparative hydrology to predictions in ungauged basins

2.3.1 Statistical methods of predictions in ungauged basins

There are two fundamentally different methods available for estimating runoff in ungauged basins. The first are statistical methods. In these types of methods the runoff signatures of interest are assumed to be random variables. Typically, the statistical methods are not based on balance equations of mass, momentum and energy. Instead, they consist of simple linear (or non-linear) relationships between runoff, and climate and catchment characteristics. The model structure is usually assumed *a priori*. The model parameters, however, are usually estimated from the data in the region of interest. In this book, the statistical methods have been assembled into three groups:

Regression methods: In the regression method, the runoff signature $\hat{y}$ of interest (for example, the flood discharge of a given probability) is estimated from catchment and/or climate characteristics x_i with sampling error ε :

$$\hat{y} = \beta_0 + \sum_{i=1}^{p} \beta_i x_i + \varepsilon + \eta$$

where there are *i* different characteristics, β_i are the model parameters (i.e., regression coefficients) and η is the model error. Many techniques are available to estimate the model parameters for the linear model (eg Mendenhall and Sincich, 2011). There are two options: use one regression model for the entire domain of interest (termed global regressions); and subdivide the domain into regions (according to Fig. 2.10b) and apply separate regression models for each region (termed regional regressions). From hydrological perspective it is important that the regression coefficients be interpreted hydrologically. This is because such interpretations increase the likelihood that the equation also applies to the ungauged catchments that have not been used in estimating the coefficients. The regression equations are very simple representations of otherwise complex process relationships. These may, in particular, involve co-evolution aspects of the catchment. The interpretation of the coefficient is therefore not necessarily mechanistic but may be based on a broader reasoning of the co-evolution of landscapes, climate, soils and vegetation.

Index methods: Index methods are based on some scaled property of the catchment. For example, the flow duration curve can be scaled by the mean annual flow. The index method then assumes that the scaled flow duration curve is uniform within a region as identified above. Another example is the Budyko curve method, where the ratio of mean annual actual evaporation to mean annual precipitation is expressed as a function of the aridity index, the ratio of mean annual potential evaporation and mean annual precipitation. The index methods reflect some underlying hydrologic principle that is not inferred from the data but from hydrological reasoning.

Geostatistical methods: The geostatistical methods exploit the correlation of runoff signatures in space. In the geostatistical approach the runoff signature of interest in the ungauged catchment is assumed to be a weighted mean of the runoff signatures in the neighbouring catchments. The weights are estimated on the basis of the spatial correlations of the runoff signatures and the relative locations of the catchments and/or the stream network. The geostatistical approach goes beyond simple spatial distance measures as they account for spatial correlations that will differ between processes and regions (e.g., longer spatial distances for low flows than for floods), and the so-called declustering property of geostatistics, i.e., the ability to give less weight to observations that are close to each other because they are correlated, so contain less information about the random variable. For clarity, in Chapters 5 and 6 simple methods based on spatial proximity are also discussed within the geostatistics section since there are practical similarities in the procedures of mapping with the geostatistical method, even though, strictly speaking, no random variables are involved.

Estimation from short runoff records: While the book is about runoff predictions in ungauged basins, there may be instances where a short runoff record is indeed available. The record may be too short to estimate the runoff signatures to a level of accuracy that is sufficient for the problem at hand. However, together with information from other catchments in the region and regionalisation methods it may be possible to exploit the information that is contained in the short runoff records. Runoff information from a neighbouring catchment is usually used to account for the temporal variability in the runoff signatures in the poorly gauged catchment of interest as a result of the runoff records in that catchment being too short.

2.3.2 Process based methods of predictions in ungauged basins

A second type of methods of estimating runoff in ungauged basins is process based methods. Process based methods are normally based on come combination of balance equations of mass, momentum and energy. Most of them are deterministic methods, i.e. without random elements. However, there are some combinations of process based methods with statistical methods as well. The model structure, in most instances, is assumed *a priori*, based on a conceptual understanding of the hydrological processes operating at the catchment scale. For the case of predicting runoff hydrographs several methods include models that are based on an understanding of hydrological processes obtained at the laboratory scale. Examples are models that use the Richards equations for estimating infiltration and subsurface water movement. Model parameters for the first type of conceptual models are usually inferred from parameters that have been found by calibration to runoff in neighbouring catchments. Model parameters for the second type of models that are based on laboratory scale governing equations are usually inferred from field data and similarity assumptions. In this book, the process based methods have been assembled into three groups:

Derived distribution methods: In this type of approach, the runoff signatures (such as floods) are estimated from precipitation signatures (such rainfall statistics). The appealing thing about the derived distribution approach is that the rainfall-runoff relationship can be formulated directly in terms of probabilities, often in an analytical way, which makes for a clear model structure. However, the model parameters may not be easy to identify in ungauged basins.

Methods based on continuous rainfall-runoff models: All the signatures (annual runoff, seasonal runoff, flow duration curve, low flows, floods) in ungauged basins can be estimated in a straightforward way if runoff hydrographs are available in that catchment over a sufficiently long period. One way of estimating these signatures therefore is to first estimate hydrographs in ungauged basins and then extracting the signatures from them. If the focus is on a particular signature, special considerations in rainfall-runoff modelling may apply, e.g., one may strive to represent low flows particularly well by the rainfall-runoff model, if one is interested in low flows in ungauged basins. This method hinges on the accuracy of runoff modelling in ungauged basins, which often justifies the use of alternative methods.

Methods that exploit proxy data: While no runoff data are available in ungauged basins, there may be other data available that may contain useful information about the runoff signatures. This method strives to make use of such data as flood marks, vegetation patterns, and a range of remote sensing products on hydrological variables such as snow and soil moisture.

2.4 Assessment of predictions in ungauged basins

2.4.1 Comparative assessment as a means of synthesis

In the comparative hydrology approach, the idea is to learn from the similarities and differences between catchments in different places, and interpret these in terms of underlying climate-landscape-human controls. In a quantitative science such as hydrology, learning comes from hypothesis testing, and the hypotheses in the context of PUB are runoff predictions in ungauged basins. Testing the predictions against independent data demonstrate that the understanding of the system is real. Assessing the predictions of runoff is therefore a scientific exercise and we can learn from the performance of such predictions. A comparative assessment provides a much wider richness of insights than testing a model at a single place. One place has only one history, whereas many places have multiple histories and hence can contribute much to our understanding.

Assessing how well the runoff predictions perform is a particular important and interesting exercise because the predictive uncertainties tend to be large relative to the magnitude of the runoff to be predicted. The uncertainties are due to many reasons. Hydrological processes have enormous spatial-temporal variability which is difficult to capture. Runoff data are only collected at a few points in the stream network, and in data poor regions any stream gauge may be far from the ungauged basin of interest. Also, there may be uncertainties in the collected data. Predictive errors of models, both statistical and process based, arise from data uncertainties, model structure uncertainties and model parameter uncertainties. Assessment of the performance provides an estimate of the total uncertainty to be expected if “blind testing” or cross validation is performed. This uncertainty estimation is complementary to other methods of estimating uncertainty such as Monte Carlo methods.

There are numerous additional insights that can potentially be gained by a comparative assessment of the performance of methods for predicting runoff in ungauged basins:

- Understanding where particular methods work best, and why, will provide insights into the co-evolution context for a wide range of processes and process interactions across scales.
- Understanding what factors control the performance will provide an opportunity to generalise the conclusions drawn from individual studies.
- It will provide researchers and practitioners useful information about the prediction performance they can expect for a particular environment with specific climate and catchment characteristics, specific data availability and a particular model type?
- Comparative assessment may therefore provide guidance on what methods to choose in a particular environment.
- It will also shed light on the value of data for predictions in ungauged basins that goes beyond the needs of a particular case study.
- Finally, identifying the various controls on the performance of estimating runoff in ungauged basins will also provide a benchmark to guide future progress on predictions of runoff in ungauged basins. This strategy will also provide a vehicle to generalize the benchmarking assessment beyond one individual study.

All of these contribute to the synthesis of predictions in ungauged basins across processes, places and scales.

To achieve this objective, a comparative assessment has been conducted, as part of the PUB initiative, which has been clustered into three main groups:

(1) Analysing the process controls on the model performance. A number of climate and catchment characteristics have been identified. A large number of catchments and modelling studies around the world have then been organised according to these climate and catchment characteristics, with a view to learning from their differences and similarities in performance in a general way. The following climate characteristics have been used in the book:

- Aridity (the ratio of potential evaporation and precipitation on a long term basis, averaged across the catchment). This is an indicator of the competition between energy and water affecting the water balance and therefore all runoff signatures.

- Air temperature (long term average air temperature, averaged across the catchment). In cold regions this is an indicator of the role of snow processes which will, again, affect all runoff signatures. Air temperature is also related to aridity, so it is not a fully independent variable.
- Elevation (average topographic elevation within the catchment). This is a composite indicator including a range of processes that are related to elevation, such as long term precipitation and hence soil moisture availability, and air temperature. In some environments there will also be a relationship between elevation and aridity and elevation and snow processes.
- Catchment area. Depending on the runoff signature examined this is an indicator of the degree of aggregation of catchment processes related to scale effects; as an indicator of storage within the catchment; and as an indicator of the amount of rainfall data that is available for runoff estimation in ungauged basins, since larger catchments tend to contain a large number of rain gauges.

(2) Analysing the predictive performance for different types of methods. The methods of estimating runoff in ungauged basins have been grouped into statistical and process based, and each of them further subdivided. Rather than evaluating specific models the focus has been on model types, so to be able to generalise beyond a particular method. An essential part of the synthesis is to go beyond individual models and focus on generic model types. For statistical methods, the model types include regressions (both global regression and regional regression), index methods and geostatistical methods. Process based methods for most signatures are much more difficult to benchmark because there is much less literature available for them, with the exception of runoff hydrographs. In Chapter 10, a range of methods for estimating the parameters of process based rainfall-runoff models have been compared, as this is an important aspect of such models.

(3) Analysing data availability. The quality of runoff predictions in ungauged basins not only depends on the hydrological setting and the regionalisation method but also, importantly, on the data that are available for the regionalisation. The final aspect of comparison therefore examines the number of stream gauges available in a particular study as an index to characterize data availability.

The three types of comparative analyses of the predictive performance of estimating runoff signatures are illustrated schematically in Fig. 2.11. The comparative assessment figures have been colour coded throughout the book to highlight the different nature of these three types of comparative assessment.

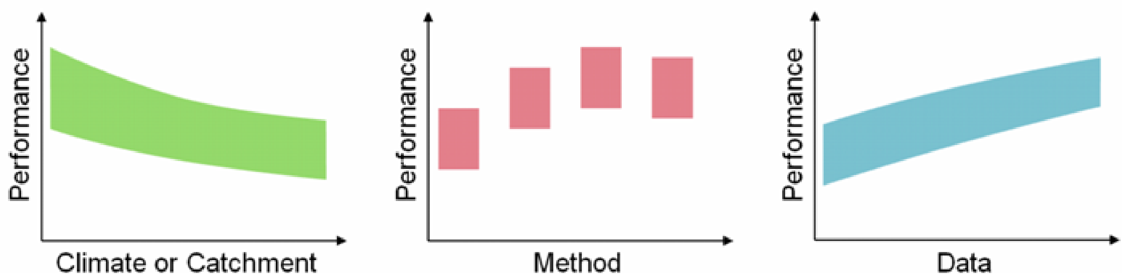

Figure 2.11: Analysis of performance of a particular runoff signature (such as annual runoff, the flow duration curve etc.) with respect to the controls.

2.4.2 Performance measures

The focus of this book is on predictions of runoff in ungauged basins. In order to assess the performance of the predictive methods, predicted runoff signatures in ungauged basins need to be compared to observed runoff signatures. This type of assessment is most often achieved by a split sample technique, breaking a dataset into two parts, using one for estimation of the model parameters and the remainder for the assessment of the predictions (Klemes, 1986). This means that the model used to estimate runoff in the ungauged basins does not use runoff information from that basin. The catchment is treated as ungauged. Only after the runoff prediction has been made are the runoff observations used for the assessment. However, local observations of climate and catchment characteristics can be used in the catchment of interest. This procedure allows for an independent cross-validation of each methodology used to provide predictions in ungauged basins, rather than enabling just a goodness of fit of a particular regionalisation method. Often, it is useful to perform this cross-validation for all catchments in a region. In this case, a leave-one-out strategy is adopted where, first, one of the catchments is treated as ungauged and the runoff signatures estimated from runoff from the other catchments in the region as well as the climate and catchment characteristics. The model's predictive ability is then tested on the catchment that was left out. The procedure is then repeated for all catchments within the region in turn, allowing for a full cross-validation and optimal use of all available data.

In each case, the model performance is assessed by comparing predicted runoff signatures in the catchments treated as ungauged basins with the observed runoff signatures. The difference is then a measure of the model performance. This "blind testing" gives an estimate of the total uncertainty to be expected. It includes all the uncertainty components including input data uncertainty, model uncertainty and parameter uncertainty (Wagener and Montanari 2011). As a consequence understanding the performance in a generalised way is a step towards reducing the uncertainty of the model predictions beyond individual case studies.

As the differences between predicted and observed are available for many catchments (and depending on the signature) for many points in time it is useful to characterise them by statistical metrics or performance measures to better compare different process controls, prediction methods and data availability settings. A number of statistical metrics are commonly used in the literature and these are summarised in Table 2.1 and 2.2. There are a number of groups of performance measures:

- Measures of bias are indicators of whether the average of the differences between predictions and observations is close to zero. Bias can be positive and negative and a bias of zero implies perfect prediction with respect to bias. It is an important aspect of model performance since it describes the mass balance error of runoff.
- Measures of random errors are indicators of spread of the differences of predicted and observed runoff signatures. A random error of zero implies perfect predictions with respect to random errors. An example is the root mean squared error which has the same units as the runoff signatures that are being compared.
- Correlation coefficients denote the strength of the association between predicted and observed runoff signatures. There are two types here (r^2 and R^2). r^2 describes what fraction of the data variability can be explained by a linear relationship with the predictions. A correlation of 1 implies perfect linear association of the observed and predicted pattern although the mean and the variability can be quite different from those of the data. R^2 describes what fraction of the data variability can be explained by the predictions themselves. R^2 of 1 implies that the predictions and the observations are identical.
- Model efficiencies are a composite measure of bias and random error. A Nash and Sutcliffe model efficiency of unity implies perfect predictions, smaller values of N-S efficiency means less perfect predictions (Nash and Sutcliffe, 1970).

Note that some of the measures are performance measures where 1 is perfect performance while others are error measures where 0 is perfect performance. In the assessment plots of chapter 5-9 performance measures have been plotted upwards, while error measures have been plotted downwards on the vertical axis.

Most performance measures can be calculated either on the basis of runoff (m^3/s) or on the basis of specific runoff ($m^3/s/km^2$). Runoff signatures tend to produce much higher correlations for runoff than for specific runoff because area is always an important predictor of runoff due to mass balance considerations.

In addition to the quantitative performance measures, qualitative reasoning can be used to help understand how close a representation the runoff predictions are to the real-world system, i.e. how realistic the model predictions are. This aspect might have to include extensive hydrological reasoning. One example is the interpretation of the coefficients in the regression equations. If they match the understanding one has of the hydrological system, they can be considered more realistic, and one would expect that they can then be extrapolated more reliably to ungauged basins. Another example is the degree to which runoff models in ungauged basins represent the flow paths with the basin of interest.

Table 2.1 Main performance measures used to evaluate the signatures in Chapter 5 to 10. For definition of level 1 and level 2 assessments see section 2.4.3. For description of performance measures see Table 2.2. Runoff signatures are as follows: Q: runoff, q: specific runoff, Q_{100}: 100yr flood runoff, Q_{95} low flow that is exceeded 95% of time.

	Level 1	Level 2	type of variability analysed
Chapter 5 Annual runoff	r^2 of Q, q, log Q, log q	NE, ANE of mean runoff	spatial
Chapter 6 Seasonal runoff	NSE, r^2 for each month	NE, ANE of range, NSE	temporal and spatial
Chapter 7 Flow duration curves	ANE of quantiles, proportion of NSE < 0.75 (NSE of quantiles)	NE, ANE of slope	temporal
Chapter 8 Low flows	R^2, r^2 RRMSE of q_{95}	NE, ANE of q_{95}	spatial
Chapter 9 Floods	RMSNE of q_{100}	NE, ANE of q_{100}	spatial
Chapter 10 Runoff hydrographs	NSE	NSE	temporal

Table 2.2 Performance measures used in the comparative assessment and symbols. $\hat{Q}_i$: estimated runoff signature at location *i*, $\hat{Q}_t$: estimated runoff signature at time *t*, Q : corresponding observed runoff, $\overline{Q}$: average observed runoff in time (or space).

Symbol	Name	Estimator	Meaning	Value for perfect per-formance	How it relates to other measures

r²	Coefficient of determination (squared correlation coefficient)	$r^2 = \frac{\left(\sum\left(\hat{Q}_i - \overline{\hat{Q}}\right)\left(Q_i - \overline{Q}\right)\right)^2}{\sum\left(\hat{Q}_i - \overline{\hat{Q}}\right)^2 \sum\left(Q_i - \overline{Q}\right)^2}$	Degree of linear association. 1 for perfect positive association, 0 if no linear correlation	1	Random error after scaling with a linear relationship
R²	Coefficient of determination	$R^2 = 1 - \frac{\sum\left(\hat{Q}_i - Q_i\right)^2}{\sum\left(Q_i - \overline{Q}\right)^2}$	1 for perfect prediction, 0 if prediction is no better than the average of the observed data, negative value would be worse.	1	Composite measure of bias and random error
RMSNE	root mean squared normalised error	$RMSNE = \sqrt{\frac{1}{n}\sum\left(\frac{\hat{Q}_i - Q_i}{Q_i}\right)^2}$	0 for perfect prediction, larger for poorer predictions.	0	Composite measure of bias and random error
RRMSE	relative root mean squared error	$RRMSE = \frac{\sqrt{\frac{1}{n}\Sigma\left(\hat{Q}_i - Q_i\right)^2}}{\bar{Q}}$	0 for perfect prediction, larger for poorer predictions.	0	Composite measure of bias and random error
NE	normalised error	$NE_i = \frac{\hat{Q}_i - Q_i}{Q_i}$	Difference between prediction and observation, scaled by the observation. 0 for a perfect prediction at one location, larger or smaller for poorer predictions.	0	$Var(NE_i) = RMSNE^2$ if prediction unbiased i.e. $\sum\left(\frac{\hat{Q}_i - Q_i}{Q_i}\right) = 0$
ANE	absolute normalised error	$ANE_i = \left\lvert\frac{\hat{Q}_i - Q_i}{Q_i}\right\rvert$	Absolute difference between prediction and observation, scaled by the observation. 0 for a perfect prediction at one location, larger for poorer predictions.	0	
NSE	Nash and Sutcliffe model efficiency	$NSE = 1 - \frac{\sum\left(\hat{Q}_t - Q_t\right)^2}{\sum\left(Q_t - \overline{Q}\right)^2}$	1 for perfect prediction, 0 if prediction is no better than the average of the observed data, negative for poorer predictions.	1	Composite measure of bias and random error

2.4.3 Level 1 and Level 2 assessments

In order to perform the comparative assessment of runoff predictions in ungauged basins, a two step process has been adopted:

Level 1 assessment: In a first step, a literature survey was performed. Publications in the international refereed literature were scrutinised for results of the predictive performance of runoff. This analysis was conducted for all the signatures: annual runoff, seasonal runoff, flow duration curve, low flows, floods, and runoff hydrographs. The Level 1 assessment is a meta analysis of prior studies performed by the hydrological community. The advantage of this type of meta-analysis is that a wide range of environments, climates and hydrological processes can be covered that go beyond what can be reasonably achieved by a single study. It is a comparative assessment that synthesises the results from the available international literature. However, the level of detail of the information provided is often limited. The results in the literature were almost always reported in an aggregated way, i.e. as average or median performance over the study region or part of the study region.

Level 2 assessment: To complement the Level 1 assessment, a second assessment step was performed, termed Level 2 assessment. In this step, some of the authors of the publications from Level 1 were approached to provide data on their runoff predictions *for individual ungauged basins*. The data they provided included information on the catchment and climate characteristics, on the method used, the data availability, and predictive performance. As in Level 1, the cross-validation performance for ungauged basins was analysed; however, information on individual catchments was now available. The overall number of catchments involved was smaller than in the Level 1 assessment, so the spectrum of hydrological processes covered in the assessment was narrower. However, the amount of information available on predicting runoff signatures in particular catchments was much higher. The Level 1 and Level 2 are therefore complementary steps, as illustrated in Fig. 2.13.

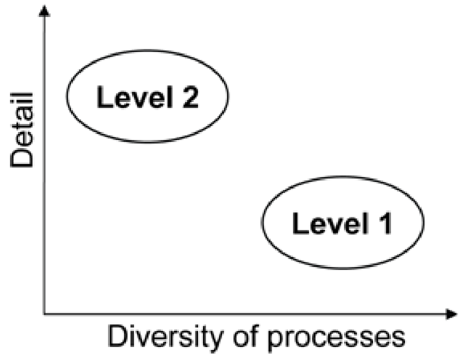

Fig. 2.12 Definition of Level 1 and Level 2 assessments. Detail relates to the amount of information available on predicting runoff signatures in a particular catchments such the predictive errors and catchment/climate characteristics. Diversity of processes relates to the spectrum of hydrological processes covered in the comparative assessment from a small diversity if only a few regions are examined to a large diversity if many regions worldwide are examined.

2.5 Summary of key points

- Catchments are complex systems that have evolved through a process of reciprocal evolutionary change of soils, vegetation, and topography, mediated by water fluxes, in response to long term climate dynamics and geologic processes. The interactions and feedbacks between these components have contributed to the generation of the diversity of interesting patterns that we see in natural catchments.
- Hydrological response signatures are the outward manifestation of the operation of these complex systems. They thus provide a window into the dynamic catchment behaviour at a range of time scales. They help us to understand the catchment system holistically.

- Comparing many catchments with contrasting characteristics in a synoptic way, defined as "comparative hydrology", will help understand the controls of the behaviour of catchments viewed as complex systems. The resulting idea is to learn from the similarities and differences between catchments in different places, and to interpret these in terms of underlying climate-landscape-human controls.
- Hydrologic similarity can be defined in terms of climate, catchment characteristics, or in terms of runoff signatures. Understanding hydrologic similarity is the basis for our ability to predict runoff in ungauged basins, extrapolating from gauged to ungauged basins within a homogeneous region, based on either statistical or process based methods.
- Runoff predictions in ungauged basins are associated with considerable uncertainty. Assessing the performance of the predictions will give an estimate of the total uncertainty to be expected, including data, model and parameter uncertainties. This method of uncertainty estimation is complementary to other methods such as Monte Carlo simulations.
- Comparative assessment of the performance of runoff predictions amongst a range of methods, and in many ungauged basins around the world, will give generalised estimates of the predictive uncertainty and a generalised understanding of the factors controlling it and thus shed light on the co-evolution of catchments, will provide guidance on what methods to choose in particular environments and why, and will thus provide a benchmark to guide any future progress on predictions of runoff in ungauged basins.
- A comparative assessment (blind testing) of the predictions of runoff signatures (annual runoff, seasonal runoff, flow duration curve, low flows, floods, and runoff hydrographs) in ungauged basins is performed in this book, as part of a synthesis across processes, places and scales, at two different levels. The Level 1 assessment is a meta-analysis from the extensive published literature. The Level 2 assessment is a more detailed analysis of numerous individual catchments from around the world, selected from the studies of the literature. In each case, predictive performance is analysed in a comparative way as a function of climate and catchment characteristics, the prediction method and data availability.

References

Abrahams, A. D. (1984), "Channel networks: A geomorphological perspective," *Water Resour. Res.*, *20*(2), 161-188, doi:10.1029/WR020i002p00161.

Arabie, P., Hubert, L.J. and De Soete, G. (eds.) (1996). Clustering and Classification. World Scientific Publishing, River Edge, NJ.

Baker, V. R., 1986. Fluvial Landforms. In: *Geomorphology from Space*, edited by N. M. Short, Sr. and R. W. Blair, Jr. NASA.

Black, P. E. (1997), Watershed Functions, *Journal Of The American Water Resources Association*, *33*(1), 1-11, doi:10.1111/j.1752-1688.1997.tb04077.x.

Bronowski, J. (1965), *Science and Human Values*, Harper & Row. [online] Available from: http://www.loc.gov/catdir/description/hc042/89045631.html

Budyko, M. I. (1974), *Climate and Life*, edited by D. H. Miller, Academic Press. [online] Available from: http://books.google.com/books?id=Ln89Y-6KwZYC

Carrillo, G., P. A. Troch, M. Sivapalan, T. Wagener, C. Harman, and K. Sawicz (2011), Catchment classification: hydrological analysis of catchment behavior through process-based modeling along a climate gradient, *Hydrology and Earth System Sciences*, *15*(11), 3411-3430, doi:10.5194/hess-15-3411-2011.

Cressie, N. (1991) Statistics for Spatial Data, Wiley New York, 872 pp

de Boer, D. H. (1992) Hierarchies and spatial scale in process geomorphology: a review. Geomorphology 4, 303–318

Dooge, J. C. I. (1986), Looking for hydrologic laws, *Water Resources Research*, *22*(9), 46S-58S.

Eder, G., M. Sivapalan, H.P. Nachtnebel (2003). Modeling of water balances in Alpine catchment through exploitation of emergent properties over changing time scales. *Hydrol. Process.*, 17, 2125-2149, doi: 10.1002/hyp.1325.

Erhard-Cassegrain, A. and J. Margat (1979). Introduction à l'économie générale de l'eau. BRGM, Orléans, France.

Falkenmark, M. and Chapman, T. (1989), *Comparative Hydrology*, *UNESCO,* Paris, France.

Gaál, L., J. Szolgay, S. Kohnová, J. Parajka, R. Merz, A. Viglione, and G. Blöschl (2012), Flood timescales: Understanding the interplay of climate and catchment processes through comparative hydrology, *Water Resources Research*, *48*(4), 1-21, doi:10.1029/2011WR011509.

Haff, P. K. (1996), Limitations on Predictive Modeling in Geomorphology, Ch. 14 in: *The Scientific Nature of Geomorphology*, Proc. 27th Binghamton Symposium in Geomorphology (B. L. Rhoads and C. E. Thorn, Editors), pp. 337-358.

Harte, J. (2002), Toward a synthesis of the Newtonian and Darwinian worldviews, *Physics Today*, *55*(10), 29-34.

Jax, K. (2005), Function and "functioning" in ecology: what does it mean?, *Oikos*, *111*(3), 641-648, doi:10.1111/j.1600-0706.2005.13851.x.

Jefferson, A., G. E. Grant, S. L. Lewis, and S. T. Lancaster (2010), Coevolution of hydrology and topography on a basalt landscape in the Oregon Cascade Range, USA, *Earth Surface Processes and Landforms*, *816*(January), n/a-n/a, doi:10.1002/esp.1976.

Jothityangkoon, C., M. Sivapalan and D. Farmer (2001). Process controls of water balance variability in a large semi-arid catchment: Downward approach to hydrological model development. *J. Hydrol.,* 254(1-4), 174-198.

Kallis, G. (2007), When is it coevolution*? Ecological Economics,* 62(1), 1–6.

Kirkby, M. J. (1978), *Hillslope Hydrology*, edited by M. G. Anderson and T. P. Burt, John Wiley and Sons.

Klemeš, V. (1986), Dilettantism in hydrology: Transition or destiny?, *Water Resources Research*, *22*(9S), 177S, doi:10.1029/WR022i09Sp0177S.

Knighton, A. D. and G. C. Nanson (2001). An event-based approach to the hydrology of arid zone rivers in the Channel Country of Australia. *J. Hydrol.,* 254, 102-123.

Köppen, W. (1936), Das geographische System der Klimate, in *Handbuch der Klimatologie*, vol. 1, edited by W. Köppen and R. Geiger, pp. 1-44, Gebrüder Bornträger.

Kumar, P. (2007), Variability, Feedback, and Cooperative Process Dynamics: Elements of a Unifying Hydrologic Theory, *Geography Compass*, *1*(6), 1338-1360, doi:10.1111/j.1749-8198.2007.00068.x.

Kumar, P. (2011), Typology of hydrologic predictability, *Water Resources Research*, *47*(July 2010), 1-9, doi:10.1029/2010WR009769.

Lvovich, M. I. (1979), World water resources, present and future, *GeoJournal*, *3*(5), 423-433, doi:10.1007/BF00455981.

McDonnell, J. J. et al. (2007), Moving beyond heterogeneity and process complexity: A new vision for watershed hydrology, *Water Resources Research*, *43*(7), 1-6, doi:10.1029/2006WR005467.

McDonnell, J.J. and Woods, R. 2004. On the need for catchment classification. Journal of Hydrology, 299, 2-3

Mendenhall, W. and T. Sincich (2011) A Second Course in Statistics: Regression Analysis.

Nash, J. E., and J. V. Sutcliffe (1970), River flow forecasting through conceptual models, *Journal of Hydrology*, *10*(3), 282-290.

Parajka, J., S. Kohnová, R. Merz, J. Szolgay, and K. Hlavčová (2009), Comparative analysis of the seasonality of hydrological characteristics in Slovakia and Austria, *Hydrological Sciences Journal*, *54*(June), 456-473, doi:10.1623/hysj.54.3.456.

Rasmussen, C. (2008). Mass balance of carbon cycling and mineral weathering across a semiarid environmental gradient. *Geochimica et Cosmochimica Acta*, 72: A778-A778.

Raupach, M. R. (2005), Simplicity, complexity and scale in terrestrial biosphere modelling, *In Franks S*, *pp*, 239-274.

Rihani, S. (2002). Complex Systems Theory and Development Practice: Understanding Non-Linear Realities, Zed Books, London, UK, 280p.

Sivapalan, M. (2005), Pattern, Process and Function: Elements of a Unified Theory of Hydrology at the Catchment Scale, in *Encyclopedia of Hydrological Sciences*, edited by M. G. Anderson, pp. 193-219, Wiley.

Sivapalan, M., G. Blöschl, L. Zhang, and R. Vertessy (2003). Downward approach to hydrological prediction. *Hydrol. Process.*, 17, 2101-2111, doi: 10.1002/hyp.1425.

Sivapalan, M., H. H. G. Savenije and G. Blöschl (2012), Socio-hydrology: A new science of people and water, *Hydrological Processess*, 26(8), 1270-1276, doi: 10.1002/hyp.8426

Sivapalan, M., S. E. Thompson, C. J. Harman, N. B. Basu, and P. Kumar (2011), Water cycle dynamics in a changing environment: Improving predictability through synthesis, *Water Resources Research*, *47*(W00J01), W00J01, doi:10.1029/2011WR011377.

Thompson, J. N. (1994), *The coevolutionary process*, University of Chicago Press.

Thompson, S. E., C. J. Harman, P. A. Troch, P. D. Brooks, and M. Sivapalan (2011), Spatial scale dependence of ecohydrologically mediated water balance partitioning: A synthesis framework for catchment ecohydrology, *Water Resources Research*, *47*, 1-20, doi:10.1029/2010WR009998.

Thornthwaite, C. W. (1931), The climates of North America according to a new classification, *Geographical Review*, *21*(4), 633-655.

Wagener, T., M. Sivapalan, P. Troch, and R. Woods (2007), Catchment Classification and Hydrologic Similarity, *Geography Compass*, *1*(4), 901-931, doi:10.1111/j.1749-8198.2007.00039.x.

Wang, D., and L. Wu (2012), Similarity between runoff coefficient and perennial stream density in the Budyko framework, *Hydrology and Earth System Sciences Discussions*, *9*(6), 7571-7589, doi:10.5194/hessd-9-7571-2012.

Winder, N., B. S. McIntosh, and P. Jeffrey (2005), The origin, diagnostic attributes and practical application of co-evolutionary theory, *Ecological Economics*, *54*(4), 347-361, doi:10.1016/j.ecolecon.2005.03.017.

Xu, Xiangyu, D. Yang, H. Lei and M. Sivapalan (2012), Assessing the impact of climate variability on catchment water balance and vegetation cover, *Hydrology and Earth System Sciences*, 16, 43–58, doi:10.5194/ hess-16-43-2012